

The Effect of Penetration Depth on Thermal Contrast of NDT by Thermography

Tsuchin Philip Chu
Anthony DiGregorio
Southern Illinois University at Carbondale
Department of Mechanical Engineering
and Energy Processes
Carbondale, IL 62901-6603
(618) 453-7003

Samuel S. Russell
NASA/MSFC
Material and Processes Laboratory
Non-Destructive Evaluation and Tribology
Branch, EH 13
Marshall Space Flight Center, AL 35812
(256) 544-4411

Introduction

Nondestructive evaluation by Thermography (TNDE) is generally classified into two categories, the passive approach and the active approach (Maldague 1993). The passive approach is usually performed by measuring the natural temperature difference between the ambient and the material or structure to be tested. The active approach, on the other hand, requires the application of an external energy source to stimulate the material for inspection. A laser, a heater, a hot air blower, a high power thermal pulse, mechanical, or electromagnetic energy may provide the energy sources. For the external heating method to inspect materials for defects and imperfection at ambient temperature, a very short burst of heat can be introduced to one of the surfaces or slow heating of the side opposite to the side being observed. Due to the interruption of the heat flow through the defects, the thermal images will reveal the defective area by contrasting against the surrounding good materials. This technique is called transient Thermography, pulse video Thermography (Hobbs 1992), or thermal wave imaging. In general, a deeper defect will be observed later and with a reduced contrast. As an empirical rule, the radius of the smallest defect should be at least one to two times larger than its depth under the surface (Vavilov and Taylor 1982).

Thermography is being used to inspect void, debond, impact damage, and porosity in composite materials. It has been shown that most of the defects and imperfection can be detected. However, the current method of inspection using thermographic technique is more of an art than a practical scientific and engineering approach. The success rate of determining the defect location and defect type is largely depend on the experience of the person who operates thermography system and performs the inspection. The operator has to try different type of heat source, different duration of its application time, as well as experimenting with the thermal image acquisition time and interval during the inspection process. Furthermore, the complexity of the lay-up and structure of composites makes it more difficult to determine the optimal operating condition for revealing the defects.

In order to develop an optimal thermography inspection procedure, we must understand the thermal behavior inside the material subjected to transient heat in order to interpret the thermal images correctly. Fabrication of finite element models of characteristic defects in composite materials subjected to transient heat will enable the development of appropriate procedure for thermography inspection. Design of phantom defects could be modeled and behavior characterized prior to physically building these test parts. Since production of phantom test parts can be very time consuming and laborious, it is important to design good representative defects. Phantom defects frequently will not function as

expected. Additionally, methods of thermography could be modeled and compared based upon the FEA modeling without performing the test.

Thermal Contrast Contour and Depth of Penetration

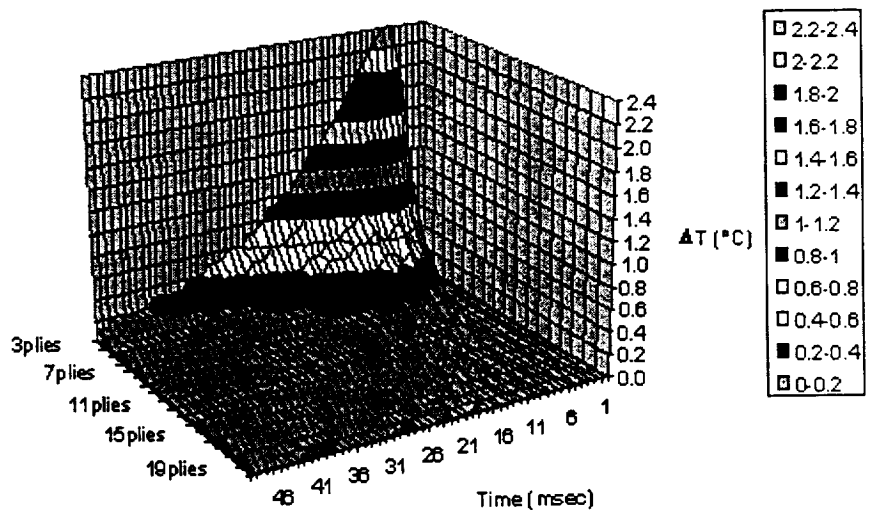
The objective of the project is to determine the optimal detection parameters and capability of the infrared Thermography inspection systems through a computational model. A finite element analysis (FEA) software was used to generate and analyze models of composite panels with defects at various depths. The results were organized and charts of thermal contrasts vs. time and depth of defects were established. These charts provide a very important set of tools to determine the inspection parameters for NDE of composite materials and structures.

To determine whether increasing the heat flux would improve the thermal contrast on the surface of the composite panel and the depth of penetration of the inspection, 4 sets of 18 finite element models were built. The results of the analysis were used to develop trends for the effects of increasing the uniform heat flux applied by the flash method. The different values of heat flux used for each of the 4 sets were 1400, 2800, 5600, and 8400 kW/m². For each of the sets, 18 different defect depths were modeled, starting at 3 ply deep and ending at 20 ply deep. All of the models used the same material properties, and they all were generated with a [0/90/0/90/0]_s laminate geometry. The size of all models is 38x 38 mm. The thickness of each ply is 0.15 mm. The element used is an 8-node isoparametric solid element (brick element). Each element is one ply thick and there are 5 elements for every quarter-inch of length in the models. The time duration under investigation is 0.05 seconds and the time between each step is 0.001 seconds. The coefficient of natural convection applied to the top surface is 58.9 W/m²-°C. The initial and ambient temperature of the composite is 24 °C. The composite panel model has a density of 1.492 g/cc and a specific heat of 1.269 J/kg-°C. The thermal conductivity for each model is 2.272 W/m-°C along the fiber direction and 0.194 W/m-°C in the directions perpendicular to the fiber and through the thickness.

The thermal contrast (C) on the surface of the panel is the temperature difference taken between two points on the surface of the model at any time step, the center of the defect (T_{def}), which has the highest temperature, and the outer sound region of the model (T_{sound}), which has the lowest temperature. The computation of the thermal contrast is given by

$$C(t) = T_{\text{def}}(t) - T_{\text{sound}}(t)$$

The variable t is introduced because thermal contrast is a function of time. The FEA software generates the Temperature vs. time (T-t) relation in a tabulated format. The thermal contrasts for all 18 defect depths are calculated for every time step and plotted on a 3D surface graph to generate the trend effects for that particular heat flux. The figure at right



shows the thermal contrast (ΔT) versus time and depth of penetration (number of plies) with heat flux of 1400 kW/m^2 . A contour plot, which is the top view of the 3D surface plot, can also be generated to show the maximum level of contrast for defects of varying depth for a specific size and material. There were four sets of graphs according to the heat flux applied.

Conclusions

The results of the FEA models have proven the software to be a useful tool. There is a practical use of FEA to improve the application of Thermography. Further study of composites will be completed with the use of FEA, since it gives better insight to what is actually happening during the inspection of the composite panel. There is a longer period of visible contrast for deeper plies with the increase of an applied uniform heat flux. Knowing this information alone is advantageous, because the period of time at which the maximum contrast occurs on the surface of the panel differs for each defect. This is according to how deep the defect resides in the material. The maximum thermal contrast is linearly proportional to the heat flux applied, because there is more energy added to the panel in the same period of time, and the capacity of the material remains the same. There is a limit to the amount of heat energy that can be added to the material before degrading the resin and weakening the material. Increasing the amount of heat flux by flashing does enhance the ability to detect a flaw, but not to the extent that it will improve the ability to find flaws deep in the composite panel. The increased period of maximum contrast allows more opportunities for the IR camera to catch the emitted image from the composite panel. The trends modeled are similar for most composite materials, therefore will be used in comparison to actual acquired data to develop more efficient inspection procedures and models of composite materials.

Acknowledgment

The author wishes to thank Mr. James Walker and Mr. Matthew Lansing, Senior Research Associates at University of Alabama in Huntsville, for their technical input on Thermography and test panel fabrication.

References

- Hobbs, C., "Transient Thermography," Sensor Review, Vol. 12, No. 1, MCB University Press, 1992, pp. 8-13.
- Maldague, X.P.V., Nondestructive Evaluation of Materials by Infrared Thermography, Springer-Verlag London Limited, 1993, pp. 3-11.
- Sun, J.G., and Ellingson, W.A., "Thermal Characterization - An NDE Method for CFCCs," CFCC News, DOE Office of Industrial Technologies, May 1998, No. 10, pp.3-5.
- Vavilov, V., et. al., "Thermal Nondestructive Testing of Carbon Epoxy Composites: Detail Analysis and Data Processing," NDT & E International, Vol. 26, No. 2, 1993, pp. 85-95.
- Vavilov, V, and Taylor, R., "Theoretical and practical aspects of the thermal nondestructive testing of bonded structures," Research Techniques in NDT, Vol. V, Academic Press, 1982, pp. 238-279.